Detection and Evaluation of Plant Stresses for Crop Management Decisions

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Abstract—The ability to quantitatively assess crop conditions using remotely sensed data would not only improve yield forecasts but would also provide information that would be useful to farm managers in making day-to-day management decisions. Experiments were conducted using ground-based radiometers to relate spectral response to crop canopy characteristics. It was found that radiometrically measured crop temperature, when compared with a reference temperature, was related to the degree of plant stress and could indicate the onset of stress. Reflectance based vegetation indices, on the other hand, were not sensitive to the onset of stress but were useful in evaluating the consequences of stress as expressed in changing quantities of green phytomass. Anatomical and physiological changes occur within plant cells when plants are stressed and increase the amount of reflected radiation. However, canopy geometrical changes may alter the amount of radiation that reaches a radiometer, complicating the interpretation of spectral response to stress. Timeliness, frequency of coverage, and resolution are three factors that must be considered when satellite-based sensors are used to evaluate crop conditions for farm management applications.

I. INTRODUCTION

THE POTENTIAL yield of any crop can be realized only when water, nutrient, and environmental conditions are optimum, and if disease and insect problems are minimized or prevented. Whenever plant growth is retarded by less than optimum conditions, the plants are said to be stressed. The word "stress", although difficult to define from a physiological point of view, is commonly used to signify any effect on plant growth that is detrimental. The term "crop condition" implies an evaluation of the degree of stress. Visual assessment of crop stress is qualitative at best, with the terms "good" or "poor" frequently used to describe crop condition.

The quantification of plant stress using remotely sensed data was a major objective of several research projects conducted under the AgRISTARS program. Although the research goal was to quantify crop stress using satellite data, it was necessary to conduct a number of experiments using ground-based radiometers. These instruments were used over controlled plots with known stress conditions and with known plant and soil parameters to obtain the data base required to relate the remotely sensed measurement to a degree of crop stress.

During the course of the experiments it became appar-

ent that a number of factors can complicate the assessment of stress when interpreting remotely sensed data. Obviously, some frame of reference is required if a numerical value is to be assigned to a stress condition. Furthermore, the spectral response of plant canopies is related to geometrical as well as physiological factors. In some cases, differences in spectral response of two plant canopies may be due to leaf orientation, not to different stress conditions. When plants are stressed leaves may droop and curl, causing geometrical as well as physiological changes that affect the radiation received by a remote sensor.

The results obtained using ground-based instruments should prove useful for improving stress assessment techniques using satellite data. A quantitative measure of stress from space platforms would not only improve our ability to forecast yields, but would also provide information which would aid farm managers in making day-to-day management decisions.

This report discusses some research results concerning the detection and quantification of plant stresses by remote means, examines some complicating factors in the interpretation of data, and assesses progress made in adapting remote sensing technology to provide day-by-day information on soil and crop conditions for use by farm operators in making farm management decisions.

II. DETECTION AND QUANTIFICATION OF PLANT STRESS

Thermal-IR techniques can be used to detect and, in some cases, quantify plant stress. Although plant temperatures can indicate the occurrence of stress, they cannot identify its cause. If transpiration is restricted because of a deficit of water (water stress) [1], or by the reduction of the number of conducting vessels by disease or insects (biological stress) [2], or by high salinity in the soil water (salinity stress) [3], the net result is an increase in plant temperature.

When plants are stressed, physiological changes that take place within leaves may alter their light absorption and transmittance properties. This, along with plant geometry changes such as wilting and leaf curl, can affect the amount of reflected and emitted radiation that reaches a remote sensor. Often, by the time stress can be ascertained by measurements of reflected solar radiation, visual signs are evident, and yield reducing damage has already occurred. Thus, plant temperatures indicate the onset and degree of stress at a particular time, whereas reflected solar measurements integrate the effects of stress over time.

A. Water Stress

The potential of using infrared thermometers to measure canopy temperatures was demonstrated over two decades ago [1], [4]. Since then, four indices, based on infrared temperature measurements, have been proposed for the quantification of plant water stress. They are: stress–degree–day (SDD) [5], [6], which is the canopy–air temperature difference measured post-noon near the time of maximum heating; the canopy temperature variability (CTV) [7], [8], which is the variability of temperatures encountered in a field during a particular measurement period; the temperature–stress–day (TSD) [9], which is the difference in canopy temperature between a stressed crop and a nonstressed reference crop; and the crop water stress index (CWSI) [10], [11], which includes the vapor pressure deficit of the air in relating the canopy and air temperature difference to water stress. Although these indices were developed to quantify water stress, they are useful for evaluating any type of stress that causes a rise of plant temperature.

In the development of the stress–degree–day, it was assumed that effects of environmental factors (such as vapor pressure, net radiation, and wind) would be largely manifested in the canopy temperature, and that the difference between the canopy temperature (T_c) and the air temperature (T_a) would be a relatively useful indicator of plant water stress. It was later demonstrated that the SDD was insufficient to assess water stress in corn [7]. Gardner et al. [7] showed that stressed corn plants were below air temperature much of the time, and suggested that corn may be more sensitive to water stress than wheat. They also suggested that canopy–air temperature differences may be soil, crop, and climate specific.

The basis for the canopy temperature variability (CTV) index is that soils are inherently nonhomogeneous, causing some areas within a field to become stressed before others. Consequently, canopy temperatures would show a greater variability as water becomes limiting than they would under well watered conditions. This variability can be used to signal the onset of water deficits [7], [12]. Gardner et al. [7] found standard deviations of 0.3°C in fully irrigated plots of corn. In nonirrigated plots, the standard deviation was as great as 4.2°C. They concluded that plots which exhibited a standard deviation above 0.3°C were in need of irrigation.

The difference in temperature between a stressed plot and a well watered plot (called the temperature stress day (TSD) by Gardner et al. [8]) can also be used as a water stress indicator. Clawson and Blad [9] tested this concept as to its usefulness for scheduling irrigations. Their corn plots were irrigated when the average of all canopy temperatures measured in the stressed plot during a particular time period were 1°C warmer than the average canopy temperatures of the well watered plot. These experiments indicated that both methods, the CTV and the TSD, could be used to evaluate water stress.

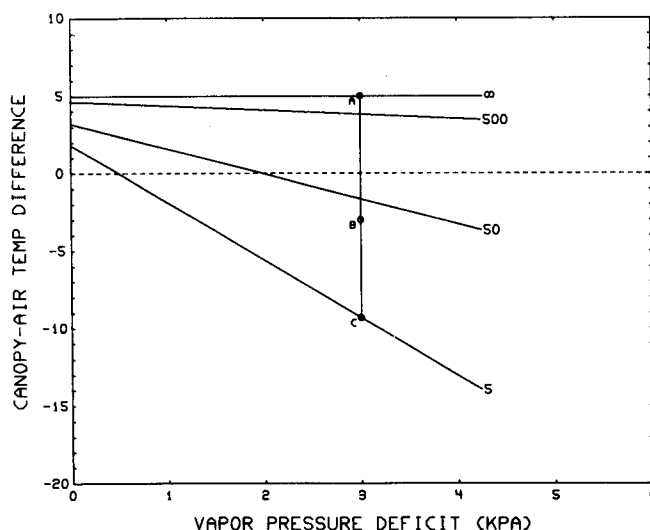The crop water stress index (CWSI) is based on the fact

Fig. 1. Theoretical relationship between the canopy–air temperature difference and air vapor pressure deficit. Numbers at the end of the lines indicate the value of the canopy resistance (r_c) used for the calculations.

that the canopy–air temperature difference is linearly related to the air vapor pressure deficit (VPD). This relation, derived from energy balance considerations, can be expressed as [4], [11]

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_c/r_a)}$$
$$- \frac{VPD}{\Delta + \gamma(1 + r_c/r_a)} \qquad (1)$$

where r_a and r_c are the aerodynamic and canopy resistances $(s \cdot m^{-1})$, R_n is the net radiation $(W \cdot m^{-2})$, ρc_p the volumetric heat capacity of air $(J \cdot m^{-3} \cdot C^{-1})$, γ is the psychrometric constant $(Pa \cdot C^{-1})$, and Δ is the slope of the temperature-saturated vapor pressure relation $(Pa \cdot C^{-1})$.

For well-watered plants the canopy resistance (r_c) is low but usually not zero [13]. Assuming that $5 \ s \cdot m^{-1}$ is representative of r_c at potential evapotranspiration, $T_c - T_a$ was calculated as a function of VPD. Results of these calculations are given in Fig. 1. Also shown are lines for $r_c = 50, 500,$ and ∞, which correspond to moderate, severe, and infinite stress, respectively. When $r_c = \infty$, (1) reduces to

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \qquad (2)$$

which shows that the upper limit of plant temperature is dependent on the aerodynamic resistance and the net radiation.

The point B in Fig. 1 represents a measured value of $T_c - T_a$. The points A and C represent the values of $T_c - T_a$ that would occur if the plants were under maximum and minimum stress, at a particular value of VPD. A crop water stress index (CWSI) was defined as the ratio of the distances BC/AC [10], [11]. The mathematical equivalent
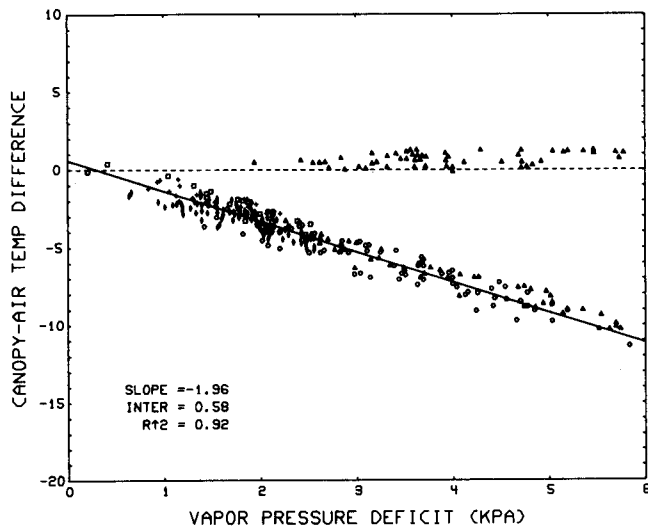
Fig. 2. Canopy-air temperature difference versus air vapor pressure deficit for well-watered plots of alfalfa assumed to be transpiring at the potential rate, and one severely water-stressed plot for which all temperature differences were positive.

Fig. 3. The near-IR/red ratio as a function of time for a dry (circles) and a wet (x) wheat plot.

$$CWSI = \frac{\gamma(1 + r_c/r_a) - \gamma^*}{\Delta + \gamma(1 + r_c/r_a)} \qquad (3)$$

can also be written [11]. The term $\gamma^* = \gamma(1 + r_{cp}/r_a)$ where r_{cp} is the canopy resistance at potential evapotranspiration. Equation (3) and the graphical calculation shown in Fig. 1 have been used by a number of authors to evaluate plant water stress in the field [3], [14]–[16]. Idso et al. [17] obtained data for alfalfa at a number of locations in the western U.S. (Fig. 2) to demonstrate the basic validity of the concept.

B. Biological, Salinity, and Nutrient Stress

Insects and disease organisms can affect the temperature of plants by disrupting the transpiration stream. Disrupting transpiration vessels has the effect of increasing the canopy resistance, and thus increasing the canopy-air temperature difference (Fig. 1). Pinter et al. [2] used a thermal-IR radiometer to measure leaf temperatures of sugar beets infected with Pythium aphanidermatum. Leaf temperatures of diseased plants averaged 2.6–3.6°C warmer than leaf temperatures of healthy plants, yet the disease could not be ascertained visually without examining the roots. Temperatures of diseased plants remained higher than healthy plants even under conditions of water stress. Results with cotton infected with Phymatotrichum omnivorum were similar. Sunlit leaves of moderately diseased plants averaged 3.3–5.3°C hotter that those on plants with no sign of fungal infection. The temperature difference between diseased and healthy plants was evident 1 day after an irrigation. As soil moisture was depleted, the diseased plants invariably wilted first.

In arid areas, increased soil salinity is a frequent consequence of irrigation. Early detection of saline areas may permit preventative measures before the crop is significantly damaged. Myers et al. [18] using ground based
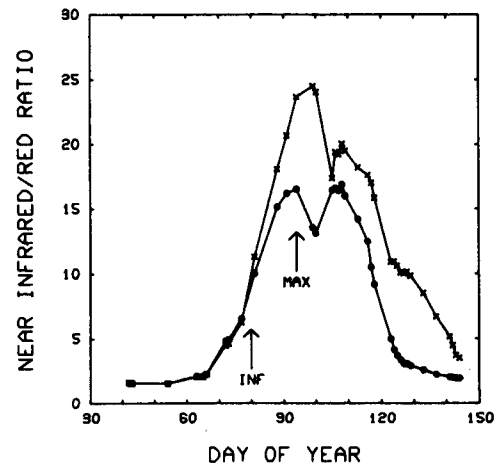
canopy temperature measurements, determined that the canopy-air temperature difference increased about 11°C with an increase of salinity corresponding to 16 dS · m^{-1}. Recently, Howell et al. [3] found that canopy temperatures were as sensitive to osmotic stress as were traditional measures, but that temperatures provided a better spatial resolution.

Howell et al. [3] determined the VPD at which cotton could maintain "unstressed" transpiration rates as related to the soil electrical conductivity in the root zone. They showed that cotton could maintain "unstressed" transpiration only if the VPD was less than 3.5 kPa. For vapor pressure deficits greater than 3.5 kPa, the plants showed symptoms of stress although soil water was not limiting.

Laboratory studies of nutrient stress showed that mineral deficiencies increased the reflectance of radiation in the visible wavelengths, whereas effects on near and middle IR reflectance varied according to the specific mineral deficiency [19]. Field measurements of corn canopies that received four nitrogen treatment levels showed that visible red reflectance increased and the near infrared reflectance decreased with decreasing nitrogen [20]. The ratio of near-IR to red radiance was related directly to the amount of nitrogen applied. Similar results have been reported for nitrogen deficient sugarcane [21].

C. Comparison of Thermal and Reflective Indices

A number of vegetation indices which are sensitive to the amount of green phytomass in the canopy can be formed from bands in the reflected portion of the solar spectrum [22]. One widely used vegetation index is the near-infrared red ratio. Fig. 3 shows this ratio as a function of time during the growing season for two plots of spring wheat, one of which was kept well watered (wet) the other given limited water (dry) [23]. Data for the dry plot are indicated by circles and for the wet plot by x. Two critical periods, the onset of stress and the maximum allowable stress, can be inferred from the vegetation index shown in Fig. 3. The well watered plot, irrigated on day 79, maintained a steady growth rate throughout the veg-
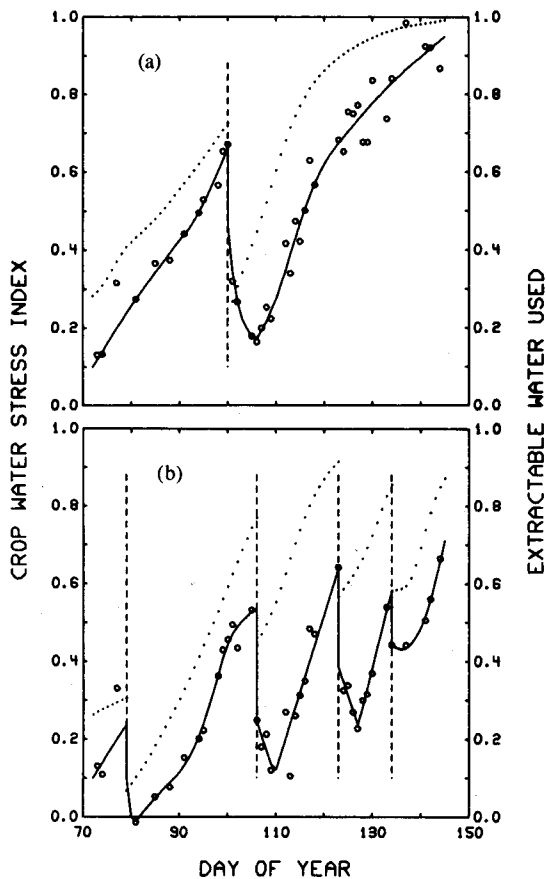
Fig. 4. The crop water stress index (circles) and the fraction of extractable water used (dots) as functions of time for (a) a dry and (b) a wet wheat plot. The dashed vertical lines indicate the dates when irrigations were given.

etative stage. Early in the season no differences were observed between the two plots, but after day 80 the growth rate of the dry plot began to decrease, as indicated by the inflection point (INF) in Fig. 3. At that time the rate of accumulation of green phytomass slowed due to lack of water in the dry plot. We interpret this as the first previsual indication of stress. Without a well watered plot for comparison, however, it would be difficult to detect the onset of stress from a time sequence of the near-IR/red ratio. Note also that the IR/red ratio for the dry plot reached a maximum on day 93 (arrow labeled MAX). At this point the net accumulation of green phytomass, as seen by the radiometer, was zero. Plant architectural changes such as wilting may have exposed more soil to the radiometer, causing a further decrease in the ratio. On day 93, visual symptoms of stress were evident, and the rate of growth was zero. After day 93, there was a net loss of green material. We interpret this point as the maximum allowable stress, because the subsequent growth rate is negative. After irrigation on day 100 the green phytomass again increased, attaining nearly the same value as the maximum reached earlier.

Fig. 4 shows the CWSI and extractable water used (EWU) [24] for the same two experimental plots. The CWSI data points are shown as circles clustering around a line drawn by eye. Smoothed values of the EWU (mea-

sured with a neutron scattering technique) are shown as dots. Irrigations are indicated by the vertical dashed lines. Both the CWSI and the EWU increased with time until an irrigation was given. At that point the EWU dropped immediately to a low value, then began to increase. The CWSI decreased, but several days were required to reach a minimum [25], after which the CWSI continuously increased signifying a stress induced reduction in transpiration [11].

To identify the values of CWSI and EWU which corresponded with a reduction in growth rate, we used the dates when the inflection and maximum points (arrows Fig. 3) were reached, and read the corresponding values of CWSI and EWU from Fig. 4. Combining the two measurements allowed the stress limits to be determined for wheat. The results indicate that, for maximum vegetative growth of wheat, the CWSI should not exceed 0.28. If the CWSI exceeds 0.52, net green phytomass can be expected to decrease. On the other hand, once the CWSI reached a minimum after irrigation, it continuously increased with time, indicating a continuous increase in stress. These results further illustrate that temperature based indices are sensitive to the onset of stress whereas the reflectance based indices can evaluate the consequences of stress as expressed in changing quantities of green phytomass.

D. Effect of Canopy Geometry on Stress Assessment

Reflectance of light from a plant canopy is a complex phenomenon which depends not only on the reflectance properties of individual leaves and stems, but also on the ways in which they are oriented and distributed. Under stress, it is likely that both of these factors will change. Laboratory measurements of leaf spectra have shown that reflectance values in the 0.4–2.5 μm region increased with decreasing leaf water content [26]. Gausman [27] demonstrated this effect using cotton leaves. He found that reflectance increased in all wavelengths as the leaves progressively dehydrated. These results can be attributed to anatomical and physiological changes within the plant cells. Crop stress also causes the geometry of the plant to change (e.g., leaf droop and curl), thus exposing different fractions of vegetation and soil (both sunlit and shaded) to the radiometer. Obviously, these changes will also affect a reflectance measurement.

The relative importance of stress induced changes in canopy architecture was studied on a cotton crop by Jackson and Ezra [28]. They measured the spectral response of a cotton canopy by repetitively traversing a radiometer over three adjacent rows of cotton. The instrument was a Barnes Multiband Modular Radiometer (MMR)[1] that has seven bands in the reflective solar and one in the thermal IR. They are: MMR1, 0.45–0.52; MMR2, 0.52–0.60; MMR3, 0.63–0.69; MMR4, 0.76–0.90; MMR5, 1.15–1.30; MMR6, 1.55–1.75; MMR7, 2.05–2.30; and MMR8, 10.5–12.5 μm. MMR bands 1–4 and 7 correspond to the The-

[1]Trade names and company names are included for the benefit of the reader and imply no preferential treatment or endorsement by the U.S. Department of Agriculture.
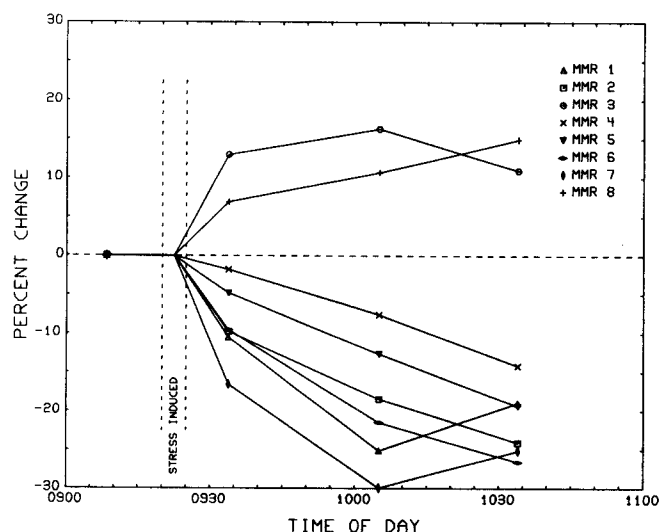
Fig. 5. Observed changes in cotton canopy reflectance and temperature as a function of time after plants were stressed by severing the main stem near the soil. Data are expressed as a percentage of energy reflected or emitted at the same time from two adjacent rows of cotton that were not stressed

Fig. 6. Reflectance factor as a function of wavelength as measured over water lily, guayule, and water.

matic Mapper bands 1-4 and 7, MMR6 to TM5, and MMR8 to TM6.

After an initial sequence of measurements, the stems of the center row of cotton were cut at a point just above the soil. Care was taken to minimize disturbance of the canopy structure. The cut plants were supported by wooden dowels that had been inserted in the soil and to which the stems had been tied the previous day. The subsequent desiccation of plants within this row was followed by comparing its reflectance and emittance with a control row.

Visual signs of wilting were apparent almost immediately after cutting. The uppermost leaves began to curl and droop first, exposing normal appearing leaves below. Then wilting progressed slowly to the lower leaves. At the end of the experiment even the lowermost leaves showed signs of wilt. As a consequence of wilting, the geometry of the canopy rapidly changed. Prior to cutting the leaves were predominately horizontal. As wilting progressed the leaves became more vertical. The laboratory analysis of Gausman [27] had indicated that reflectance increased in all wavelengths with increasing water stress due to physiological changes of the leaves. Field results indicate that the reflectance may increase at some wavelengths and decrease at others, depending on the geometry changes that accompany stress. The data in Fig. 5 show that, for this variety of cotton, geometry changes play a major role in determining reflectance properties of canopies. The reflectance of six of the seven reflected solar bands decreased as the cotton leaves dehydrated and the leaf angles changed from horizontal to vertical. Our explanation is similar to that of Holben et al. [29] in that, due to leaf droop, first surface reflections were scattered into the canopy with less radiance reaching the sensor held above the canopy. For the six bands, geometric effects overshadowed the increased reflectance that occurred due to physiological changes.
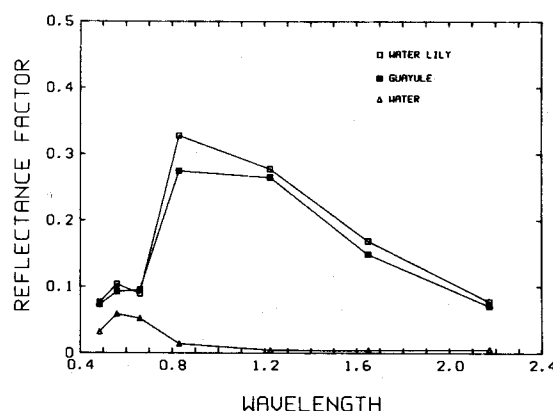
Reflectance in the red (0.63-0.69 μm) showed a net increase. The same geometrical factors were active, but the physiological changes were apparently greater. Radiation in this band (known as the chlorophyll absorption band) is absorbed by green leaves and provides the energy to combine carbon dioxide and water in the complex biochemical process of photosynthesis. In a recent review, Krieg [30] concluded that the first effect of a reduction in water availability would be a reduction in this biochemical process which would subsequently trigger the closure of stomata to reduce the exchange of carbon dioxide and water with the atmosphere. Our hypothesis is that the sudden interruption of transpiration immediately affected the photosynthesis process causing some of the red radiation that was previously absorbed to be reflected back to the environment.

On a percentage basis, the visible bands reacted as rapidly to a suddenly induced stress as did the temperature (Fig. 5). A water absorption band (2.05-2.35 μm) decreased by 17 percent within 10 min of a suddenly induced stress, whereas the red band (0.63-0.67 μm) increased by about 12 percent within the same time period. The near-IR (0.76-0.90 μm) showed the least percent change. This result is contrary to the results of Holben et al. [29] who found that the near-IR was the most sensitive to stress. In general, our results support the statement of Knipling [26] that the visible reflectance region is as sensitive to stress as is the near infrared region. However, in the visible region the reflectance values are sufficiently small that stress caused changes may not be detectable in an operational mode.

Although the reflectance factor for water in all TM bands is low (Fig. 6), the mid-IR bands (1.55-1.75 μm and 2.05-2.35 μm) are proportedly sensitive to liquid water in plant tissues. On this basis, one could assume that these bands would be useful in detecting water stress in plants. Yet, even when liquid water is present in a scene, the geometry of the scene components can be the dominant factor and can cause confusion in interpreting the data. For example, the bidirectional reflectance factor was measured over a water surface containing water lilies (Nuphar luteum Sibth. & Sm.) and over a stand of the drought

adapted desert shrub, guayule (*Parthenium argentatum* Gray). The water lily leaves covered about 80 percent of the surface area, leaving about 20 percent water exposed. The guayule shrubs were about 0.5 m tall, approaching 80–90 percent cover, and in need of water. At first glance one would think that the reflectance factor for the mid-IR bands over the water lily would be small due to absorption by the water surface and the liquid water in the large green leaves. However, the reflectance factor (measured at nadir) for water lily was greater than for guayule in all bands except the red (Fig. 6). The flat water lily leaves caused radiation to be reflected upward toward the radiometer, whereas the guayule canopy caused more radiation to be scattered horizontally than vertically. This extreme case demonstrates the fact that canopy geometry must be accounted for when interpreting reflectance factor data.

III. REMOTE SENSING AS A FARM MANAGEMENT TOOL

Thermal infrared radiometry is extensively used by researchers for plant water stress assessment and is beginning to be used by farm operators. At present, portions of fields are surveyed with hand-held instruments that display surface temperature. The degree of stress is inferred by comparison with other fields or by combining the temperatures with ancillary data such as air temperature and vapor pressure. Surface temperatures derived from satellite data have been used for qualitative stress assessment in a research mode, but operational systems have not yet been developed. Using ground based instruments to cover an entire farm is prohibitive from the point of view of time and manpower requirements.

Reflected solar radiation has been extensively measured using hand-held and boom-mounted instruments for research purposes. Satellite data are being used for yield forecasting and qualitative crop condition assessment. Vegetation maps derived from NOAA's AVHRR data have been produced for the continent of Africa [31], and are routinely produced for the U.S. [32]. This type of information is very useful for detecting large scale vegetation changes but is not sufficient for providing crop condition assessment at the farm field level. In order to accomplish the latter, problems of timeliness, frequency of coverage, and spatial resolution of a space-based system must be addressed.

A. Timeliness

Timeliness is perhaps the most important requirement for a farm management remote sensing system. Fig. 7 is a hypothetical relation that shows how the usefulness of remotely sensed data decays with time. To obtain maximum usefulness, the data must be available within minutes. This may appear extreme, but farm operations must be carried out when crop conditions demand. A remote sensing system that required, say, 5 days after acquisition for data delivery would be essentially useless for indicating when to irrigate, because yield reducing damage would have occurred by the time water could be applied. A remote-sensing system for farm management would have an
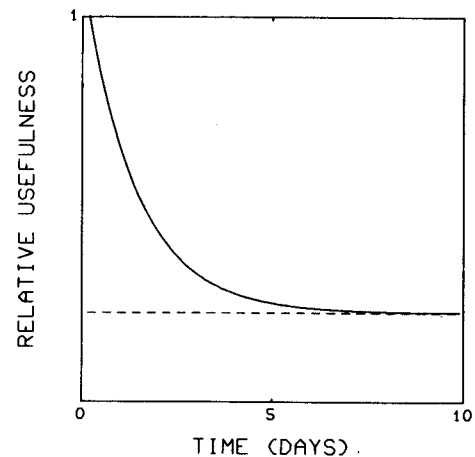

Fig. 7. Relative usefulness of remotely sensed data to farmers in relation to time from acquistion to delivery in usable form.
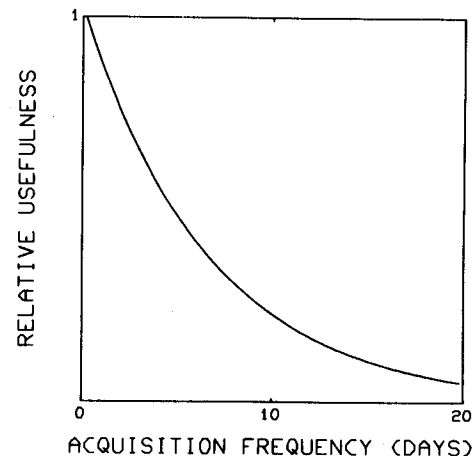

Fig. 8. Relative usefulness of remotely sensed data to farmers in relation to frequency of coverage.

optimum data delivery time of minutes, and a maximum time of a few hours.

B. Frequency of Coverage

Frequency of coverage is another important aspect. Fig. 8 shows a hypothetical relationship between usefulness and frequency. For farm management, the maximum usefulness would obtain if continuous coverage were available. During the growing season crop conditions continously change. In arid areas, irrigation may be required every 7 to 20 days. A system with a 16-day repeat time would provide little useful information. Also, cloud conditions may increase the time period between acquistions. Continuous coverage would be the optimum, with once a day coverage as a minimum.

C. Resolution

The resolution requirements for a farm management system are dependent upon the particular application for the data. For a farm with relatively uniform soils and a minimum field size of about 40 acres, the 30 × 30 m resolution of a sensor such as the Thematic Mapper may be

adequate. However, this is usually not the case. Many fields are considerably smaller than 40 acres, and soil heterogeneity across fields causes plant growth differences. As an example, during irrigation, areas with low water infiltration may not have the root zone replenished with water, whereas areas of high intake would. The irrigation program for that field would probably be decided on the basis of availability and cost of water and the current crop. A farmer may decide to over irrigate the high intake areas to assure good crop development over the entire field. Under limited water conditions the high intake areas may be used as the indicator of when to irrigate with the lower yields on the other areas accepted. Considering a number of factors, it appears that a resolution of 5 × 5 m would be optimum, with 20 × 20 m acceptable, if sensor design constraints will not allow a smaller figure.

IV. Concluding Remarks

Methods for detecting and quantifying crop stress using ground-based instruments are reasonably well developed. The identification of the cause of stress remains ambiguous. Water stress, being more ubiquitous, is usually the first suspect when stress is detected. However, nutrient deficiencies may cause stress symptoms that can be confused with water stress. When stress is caused by more than one factor, remotely sensed data may not provide enough information to identify the factors. For example, spectral detection of nutrient deficiencies have been demonstrated only when they were known to exist. Little, if any, work has been reported that specifically identified a nutrient deficient crop when the cause of the stress was not known beforehand. Similar statements would hold for biological and salinity stress detection. It is obvious that additional research will be required to resolve this problem.

The effect of canopy geometry on spectral response has been long known, but studied relatively little. A number of models are available that demonstrate the result of canopy architectural changes. However, the measurement of leaf angles required to characterize the canopy geometry in a field crop is difficult and tedious. The comparison of the reflectance values for water lily and guayule discussed in a previous section clearly demonstrated the importance of canopy architecture in determining the spectral response of crops. This complexity should not be ignored.

Reaching the goal of quantitatively assessing stress from space platforms will also require continued research. The problem of correcting for atmospheric effects on remotely sensed data has, and is being, addressed by several research groups. Until adequate methods for these corrections are made operational, stress assessment from space will remain largely qualitative.

Finally, the utilization of data from space platforms for aiding farm operators in day-to-day management decisions has yet to be realized. Although the benefits to agriculture of space technology have been expounded since the launch of the first Landsat satellite and have been very beneficial in some areas, they have not yet materialized for farm management. No space system is now in place that can provide data concerning crop conditions with the frequency of coverage, and resolution in time to initiate remedial procedures before yields are significantly reduced.
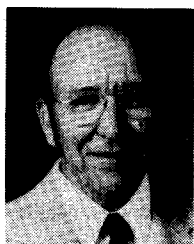
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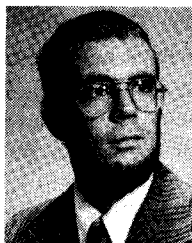
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